7B.2 TROPICAL CYCLONE RAPID INTENSIFICATION: PATTERNS RELATED TO GEOGRAPHY, TIME OF SEASON, AND STORM CHARACTERISTICS

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1. INTRODUCTION

Hurricane rapid intensification has been identified by the National Hurricane Center as a top priority for research (Rappaport et al. 2009). Kaplan et al. (2010) described patterns of rapid intensification occurrence in the Atlantic from 1989 to present, especially with respect to initial wind speed, geographic distribution of intensification events of different intensity, and time of season. They related these occurrences to several atmospheric variables in an empirically derived predictive model.

Like some other authors, Kaplan et al. (2010) defined rapid intensification as 30 kt increases within 24 h though they also explored using 25 and 35 kt thresholds. I will conduct parallel analyses of both intensification events (IE) involving 24 h increases of 15 kt, and of rapid intensifitcation events (RIE) of 30 kt. Although not as dramatic as 30 kt, intensification at 15 kt is sufficient to increase a hurricane from Saffir-Simpson category 1 to 3 in as little as 36 h.

Although attempts at modeling rapid intensification are underway, the tropical cyclone literature is still lacking a basic descriptive study of patterns of intensification occurrence across the North Atlatnic basin. The overall approach of this paper will be to describe patterns of IE and RIE concentration into particular geographical regions, portions of the hurricane season, and times within cyclone life cycles, and their disproportionate occurrence when cyclones are exhibiting particular other characteristics. I will focus on the onset of intensification and rapid intensification events, and test the hypotheses that IE or RIE inceptions are related to: (1) geographical location; (2) date during the hurricane season; (3) age of storm; (4) current sustained wind speed; (5) preceding trends of intensity (wind speed and central pressure); (6) speed of forward movement; and (7) time of day.

The likelihood of a cyclone beginning an IE or RIE are expected to vary geographically because of geographic variations in factors that are thought to control storm intensity, such as sea surface temperature, relative humidity, and upper tropospheric thermal structure (which influence potential intensity; reviewed in Camp and Montgomery 2001), depth of the oceanic surface mixed layer, wind shear, etc.. Under the simple assumption that intensification of cyclones is generally enhanced by the same environmental variables (perhaps increased when optimal values are aligned) that stimulate cyclone formation and life span, I hypothesize that IE and RIE occurrence will mirror the overall ~10 September peak of Atlantic tropical cyclone occurrence. Because a cyclone that has just formed is likely to be in a region of favorable environmental conditions, IE and RIE inceptions are expected to be especially frequent in cyclones immediately after formation. Likewise, because stronger cyclone winds should generally indicate a more favorable environment than do weaker winds even for systems that are not currently in an IE or RIE, non-intensifying systems that have faster winds are predicted to be more likely to begin IE and RIE than those with slower winds. Because mildly increasing winds (still below the IE or RIE threshold) are more likely to indicate favorable conditions than are weakening winds, onset of IE and RIE are predicted to be more likely when recent trends in wind speed are positive and/or central pressure are negative. Fast moving storms might be less likely to intensify if their movement causes structural disruption, or more likely if the speed of forward motion somehow reinforces the storm's dynamical circulation at the location of maximum sustained wind speed. Finally, studies that have shown time of day effects in cyclone occurrence (Konrad 2001), in extent of central dense overcast (Kossin 2002), or in pre-landfall wind speed changes (Yaukey 2011) suggest that variations in intensification may occur on this time scale, although they do not lend themselves a priori to predicting a peak hour.

2. METHODS

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Tropical cyclone observations were obtained from the National Hurricane Center's official record for the Atlantic basin, HURDAT (www.nhc.noaa.gov/pastall.html). This record includes location, maximum sustained wind speed, and minimum central pressure. HURDAT includes all named systems, i.e. all systems that reached tropical storm strength (wind speed 17.5 ms^{-1}), but generally includes observations of each system before and after they exhibited these speeds, starting at the time of cyclogenesis and often ending with the cyclone's disintegration. Because observations of depression stages appeared to be less common prior to 1950, I only used observations made between 1950 and 2009. In the earlier years of the dataset, central pressure observations were often omitted as well; thus, those analyses below utilizing central pressure are more representative of the most recent decades. Observations of systems that were over continental mainlands were removed via consultation of storm track maps at the Unisys website (www.weather.unisys.com/hurricanes); I also referred to Google Earth (http://www.google.com/earth/index.html) when higher resolution was necessary. Observations of cyclones that had returned to sea after landfalls on continental mainlands or Greater Antillean Islands were excluded from the analysis until they regained their pre-landfall wind speed. This was intended to exclude intensification events that merely represented a cyclone recovering at sea from the recent passage over land. The samples for areas that commonly lie down-track of land masses (e.g., the southeastern Gulf of Mexico) were more limited by this measure than were other regions.

I will compare the frequency distribution of IE or RIE among levels of an explanatory variable to the overall distribution of HURDAT observations among those levels. After basic description of geographic and within-season patterns, I will conduct statistical tests in which I eliminate serial correlation within the IE and RIE data by using only one observation from each, the observation made at the beginning of the intensification event. For two IE (RIE) events to be recorded from the same cyclone, I required the end of the first to be separated by at least 12 h from the start of the next, with no 24 h period of 15 kt (30 kt) increase linking the two. Because they were not candidates to have experienced an IE or RIE *inception*, I also removed all observations of systems that were already experiencing an IE or RIE from the null data set. Treating the overall HURDAT dataset as the expected null distribution rather than as a second sample of observations avoided the elevation of significance levels that would occur because of the extremely large sample size of HURDAT (>8000 observations would make many trivial patterns significant), and removed the need to be concerned with serial correlation among the null data. The same critical values apply in a chi-squared test in this scenario as if the null distribution were considered a separate sample. I chose not to use methods of dealing with serial correlation that rely on adjusting degrees of freedom because of the difficulty of adapting them to chi-squared analyses.

Geographical analyses compared cyclone occurrence between the Gulf of Mexico, Caribbean Sea, and in four subdivisions of the open Atlantic Ocean separated by the 60th meridian and 20th parallel. Although the resulting southwestern quadrant was relatively small due to its proximity to the Caribbean Sea, I chose these divisions so that each of the other Atlantic quadrants would be comparable in size, and so that the deep tropics (<20^0N) would be distinguished from other areas. I analyzed the timing of IE inceptions among 15-d divisions of the hurricane season, the timing of onset relative to storm age (number of 6 h intervals since cyclogenesis), storm sustained wind speed at time of observation, changes in wind speed and central pressure over the preceding 6 h, forward speed of the cyclone, and time of day. For most analyses, all tropical and substropical cyclones between June and Novemer at ≤ 50^0N that had reached tropical depression status and were not classified as extratropical were used. In several tests where the inclusion of baroclinically enhanced or other midlatitude cyclones was expected a priori to unacceptably complicate the analyses, the sample was restricted to observations made at ≤ 30^0N; these are so noted.

3. RESULTS

A total of 5339 observations in the HURDAT data set since 1950 (June to November, ≤ 50^0N) were of cyclones undergoing intensifications of ≥ 15 kts/ 24 h, amounting to 31% of all the observations of tropical and subtropical cyclones of depression strength or stronger. A total of 1977 (12% of total) were rapidly intensifying at 30 kts/ 24 h . The greatest 24 h increase recorded was by Ethel in 1960, which recorded a 100 kt increase in wind speed over just 18 h, followed by Wilma in 2005 (95 kts in 24 h) and Felix in 2007 (85 kts in 24 h).

Cyclones that had recently returned to sea were biased by the study protocol against producing IE and RIE inceptions, which were not logged until cyclones regained pre-landfall strength. When all such cyclones were also removed from the null (non-intensifying) data for consistency, this left IE comprising 36% of cyclone observations, and RIE 13%. I applied this exclusion of cyclones from the null data while they recovered from landfall throughout the analyses that follow.

To test for the statistical significance of variation in IE and RIE occurrence, serial correlation among HURDAT observations was overcome by confining analyses to a single observation per IE or RIE, the observation at the onset of the event. These analyses therefore addressed the likelihood of an observation constituting the beginning of an IE or RIE.

3.1 Geographic Patterns

Likelihood of a cyclone beginning an IE or RIE was compared among six regions: the Gulf of Mexico, Caribbean Sea, and four quadrants of the remaining North Atlantic separated by the 20th parallel of latitude and the 60th meridian (Fig. 1). Over half of the IE onset events occurred in just two of these, the northwest Atlantic and southeast Atlantic. The distribution of IE onsets differed from the expected distribution derived from the overall HURDAT data set (χ^2 = 88.9, n = 696 IE inceptions, df = 5, p < 0.0001). Most of the deviation from the null distribution was created by the paucity of IE in the northeast Atlantic (44% of the total χ^2 value), and their abundance in the Gulf of Mexico (27%). RIE inceptions were likewise distributed differently among the six regions than were cyclone observations overall (χ^2 = 78.5, n = 310 RIE inceptions, df = 5, p < 0.0001). Paucity of RIE in the northeast Atlantic contributed 41% of the χ^2 statistic, while high RIE incidence in the Gulf of Mexico and Caribbean Sea each contributed another 21-24%.

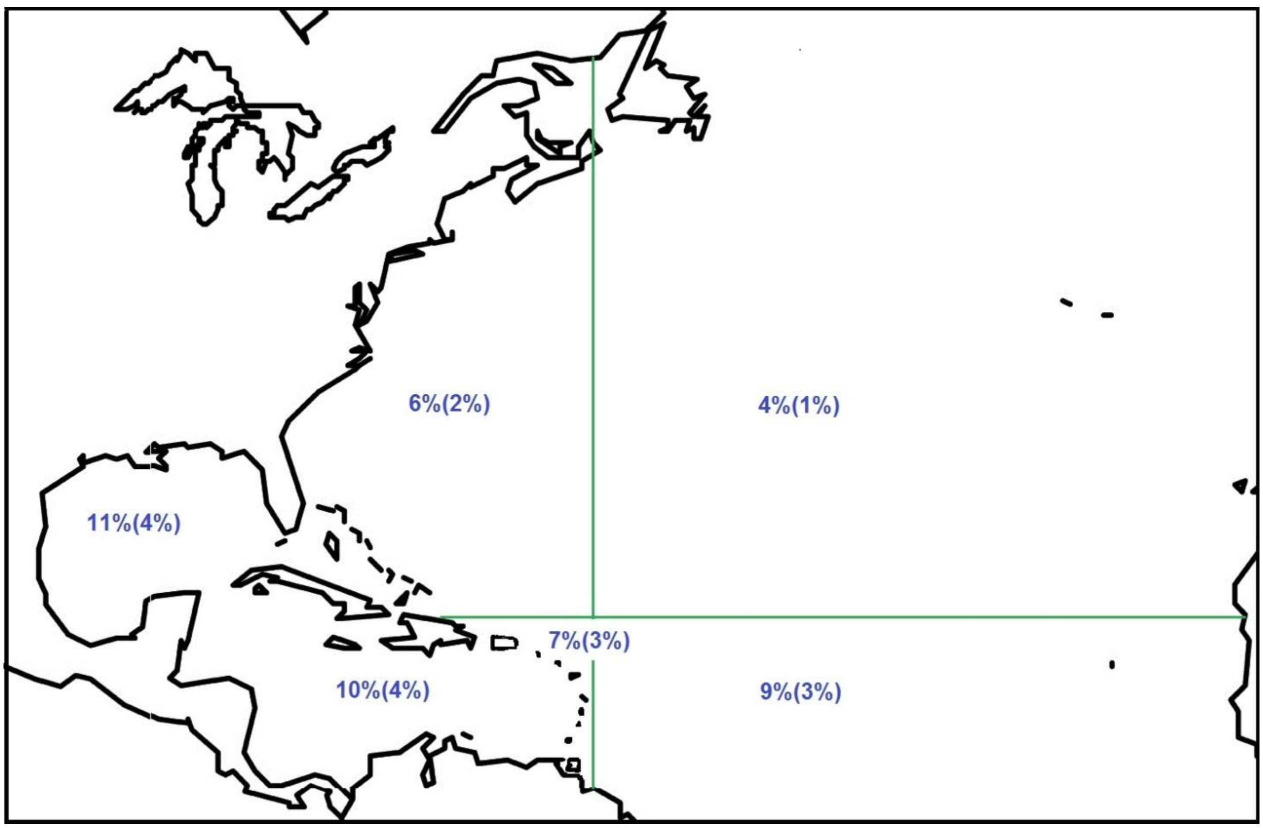

Figure 1. Percent of cyclone observations that were the inceptions of intensification events in different regions of the North Atlantic. Numbers refer to cylones beginning increases of ≥15 kts (30 kts) in 24 h.

To determine whether geographical differences were driven merely by existence of weakening storms in the middle and high latitudes, the analysis was repeated while excluding storms north of 30^{0}N, all of which were entirely in the northwest and northeast Atlantic quadrants. Below 30^{0}N, IE onset events were still unevenly distributed among the six areas (χ^2 = 16.5, n = 565 inceptions, df = 5, p = 0.0055), as were RIE inceptions (χ^2 = 19.8, n = 273 inceptions, df = 5, p = 0.0013). For IE, 41% of the test statistic was produced by high values in the Gulf of Mexico, and 35% by low rates of inception in the northeast Atlantic. For RIE, low values in the northeastern Atlantic contributed 38% of the test statistic, and elevated occurrence in the Gulf and Caribbean contributed 23-26% each.

3.2 Seasonal Patterns

The percent of cyclone observations that were IE inceptions did not peak in September when the overall peak of the hurricane season occurs, but in the consecutive 15 d periods from 16 June to 15 July (Fig. 2). Variation among 15 d periods across the season was marginally significant (χ^2 = 18.0, df = 11, p = 0.0819). RIE inceptions peaked during the same two 15 d periods, but season-long variation did not approach statistical significance (χ^2 = 8.7, df = 11, p = 0.6474). If early season storms were especially confined to the deep tropics, this might explain a June-July peak; instead only 12% and 32% of observations were at ≤20^{0}N in the late June and early July peak periods, both below the season-long mean of 34%.

If some 15 d periods had more observations from intensification-prone geographical regions than did others, then the seasonal variation in IE inceptions might be due to seasonal variation in the locations of storms. To address this, I adjusted the chi-squared expected values of each 15-d subsample to reflect its regional makeup, calculating how many inceptions might be expected based upon the proportions of observations from different regions and the mean inception rates in those regions, calculating a weighted mean. The relative sizes of the weighted means for each 15 d period compared to the others were used to adjust their original expected values proportionally up (for periods with more observations from inception-prone regions) or down (fewer). This procedure did weaken the 15 d variation in IE inception rate (becoming χ^2 = 13.6, df = 11, p = 0.2579); RIE continued to show little variation across the 15-d periods (becoming χ^2 = 9.8, df = 11, p = 0.5505). Thus, it is likely that seasonal variation in the locations of storms may explain much of the seasonal pattern of IE.

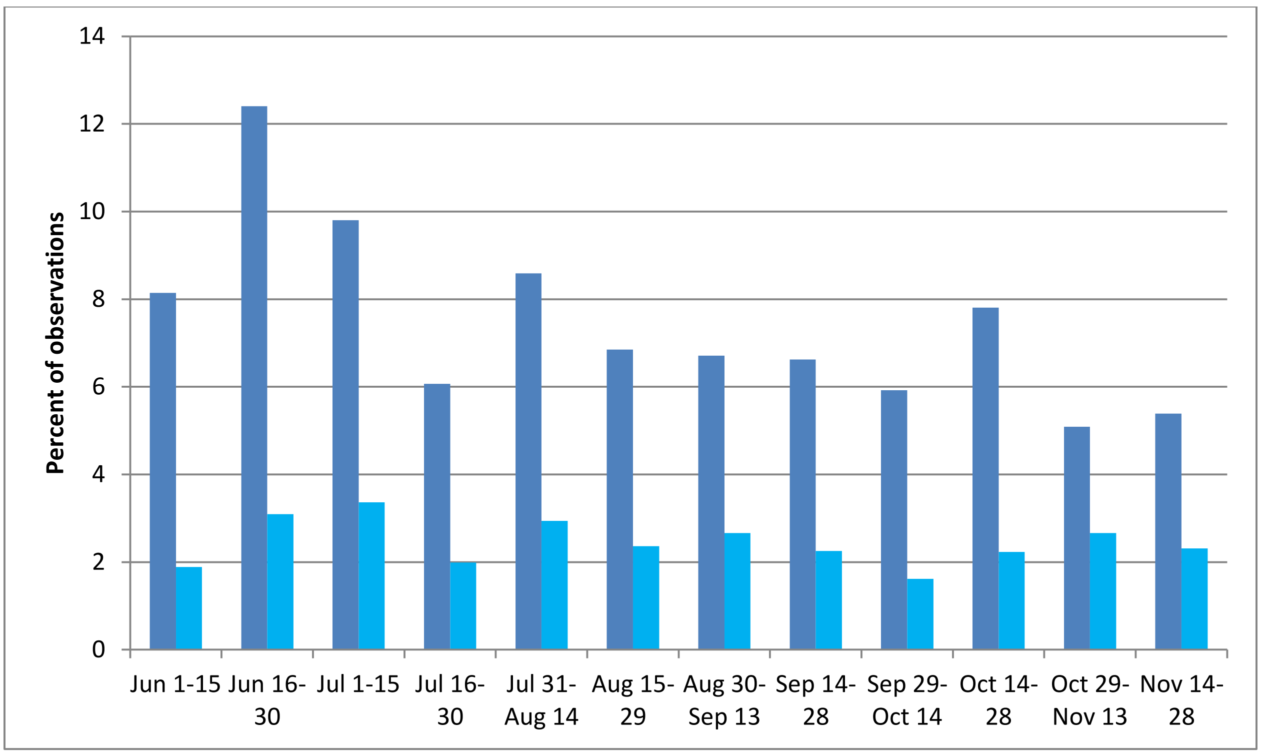

Figure 2. Percent of cyclone observations that constitute the beginning of intensification events at different times within the hurricane season. Dark blue bars indicate intensification events of 15 kt/24 h, light blue of 30 kt/24 h. Each bar has n ≥ 340.

3.3 Age of Cyclone

Intensification events usually took place at or shortly after cyclogenesis (cyclogenesis was taken as the first HURDAT entry; Fig. 3). At cyclogenesis 28% of observations were IE inceptions; this fell steadily to 9% 24 h later, and sank to 5% at 48 h. In all, 54% of all IE began in that first 24 h (first 5 observations), and the oldest cyclone to spawn an IE was 20 days old. The distribution of IE inceptions among the first twelve 6 h intervals differed from the null expectation (χ^2 = 217.1, df = 11, p < 0.0001).

The peak incidence of RIE inceptions (8%) was also at cyclogenesis. They declined thereafter, although more eratically than did IE, but constituted <3% of almost all 6 h age intervals after the 10^{th}. Forty three percent of RIE occurred in the first five observations, and the oldest cyclone to begin an RIE was 13 d old, occurring in two different cyclones. RIE inceptions were distributed differently than were null observations among the first dozen 6 h intervals (χ^2 = 38.4, df = 11, p < 0.0001).

From another perspective, a tropical cyclone in the Gulf of Mexico that was well into its life (e.g., a "Cape Verde" cyclone) was much less likely to start an IE there than one that had just formed within the Gulf: only 5% of observations of storms in the Gulf that were already > 7 d old were IE inceptions, whereas 48% of newly formed storms (first HURDAT observation) were (3% and 16% respectively for RIE).

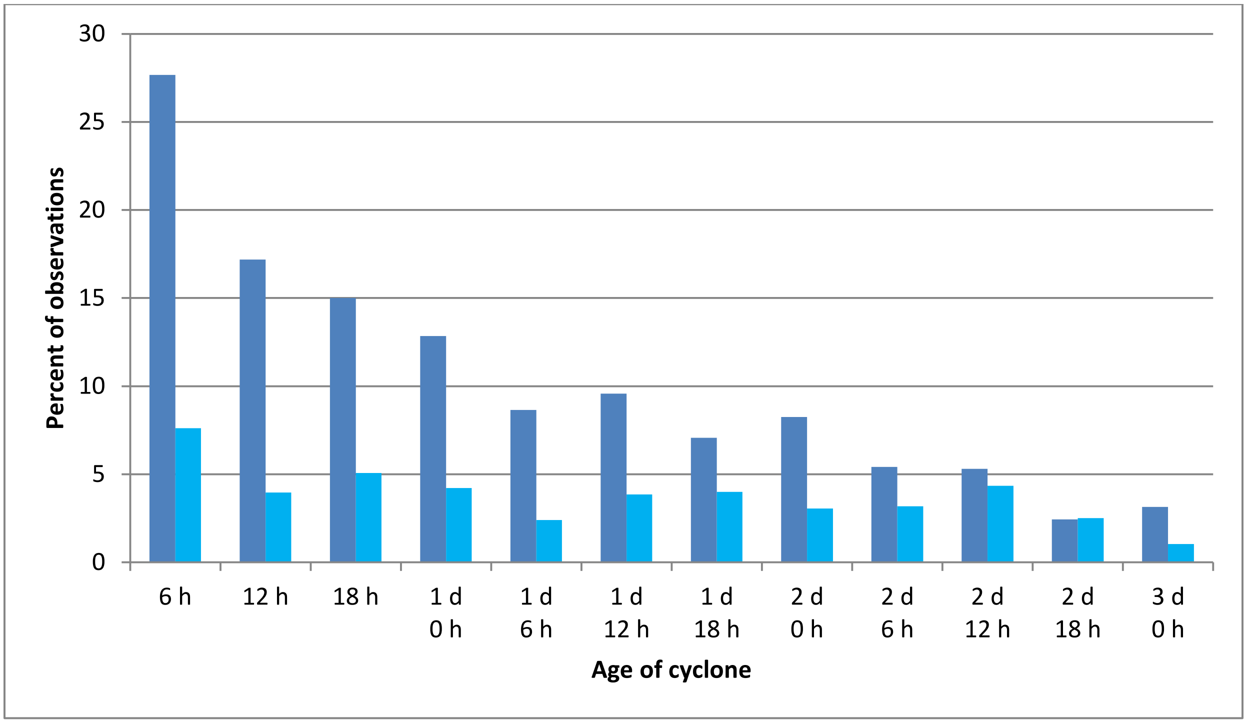

Figure 3. Percent of cyclone observations that constituted inceptions of intensification events, in relation to age of storm (up to 3 d). Medium blue are intensification events of 15 kt/24 h, light blue are 30 kt/24 h. Each bar has n ≥ 280.

Because some cyclones move into the midlatitudes late in life, it is possible that part of the decline of IE inceptions with advanced storm age could be due to the systems moving into less favorable environmental conditions (colder oceans, etc.). To address this, I repeated the analyses using only observations at ≤ 30^0N. IE inceptions at these latitudes continued to be most numerous at cyclogenesis, and to differ from the age distribution of cyclone observations overall (χ^2 = 172.4, df = 11, p < 0.0001). These patterns were true of RIE at these latitudes as well (χ^2 = 30.4, df = 11, p = 0.0014).

Apart from this latitudinal effect, it is more generally possible that observations of young or old cyclones come disproportionately from particular regions. For instance, the southeast Atlantic may have fewer old cyclones because it does not receive pre-existing tropical cyclones from farther east. To address whether the age effect was caused by storms of different ages being concentrated into different regions, I adjusted the chi-squared expected values for the age analysis to reflect the regional makeup of each age's sample, following the procedure used to above to assess regional influence on seasonal patterns. The chi-squared value remained highly significant for IE (χ^2 = 208.5, df = 11, p < 0.0001) and RIE (χ^2 = 34.9, df = 11, p = 0.0003). Likewise, any age differences among regions did not appear to account for much of the region variation in intensification (reported above); after performing the same sort of adjustment of expected values in the regional comparison to account for age differences, the chi-squared test statistic remained strongly significant for both IE inceptions (χ^2 = 15.4; df = 5, p = 0.0087) and RIE inceptions (χ^2 = 24.9; df = 5, p = 0.0001).

3.4 Wind Speed at Onset of Intensification

Tropical cyclones were most likely to begin IE when winds were relatively weak. However, peak inception rates did not occur at the lowest wind speeds examined (20 and 25 kt), but at slightly higher 30 kt winds. While inception rates declined at higher wind speeds, a second smaller peak was evident at c. 70 kts, though with inception rates less than one third the magnitude of the first.

I will refine this analysis by breaking the record into cyclones at the time of their cyclogenesis, and older cyclones. Cyclones that had 35 kt winds at the time of formation (their first HURDAT observation) were the most likely to rapidly intensify from that point forward (Fig. 4). Cyclones that had winds of 20, 25, 30, and 35 kts at cyclogenesis differed in their likelihood of starting an IE (χ^2 = 8.0, df = 3, p = 0.0469; other speeds were excluded because of small sample sizes). The high number of 35 kt observations that were IE inceptions contributed most (77%) to the chi-squared value. RIE also peaked at 35 kt in a parallel test (χ^2 = 14.8, df = 3, p = 0.0020), in which the high 35 kt values contributed 51% of the test statistic. However, expected values were problematically low in the RIE test. Inception rates appeared to fall at higher wind speeds; when observations with 40-60 kt wind speeds at cyclogenesis were lumped to overcome small sample sizes, their inception rate was not as high as for 35 kt.

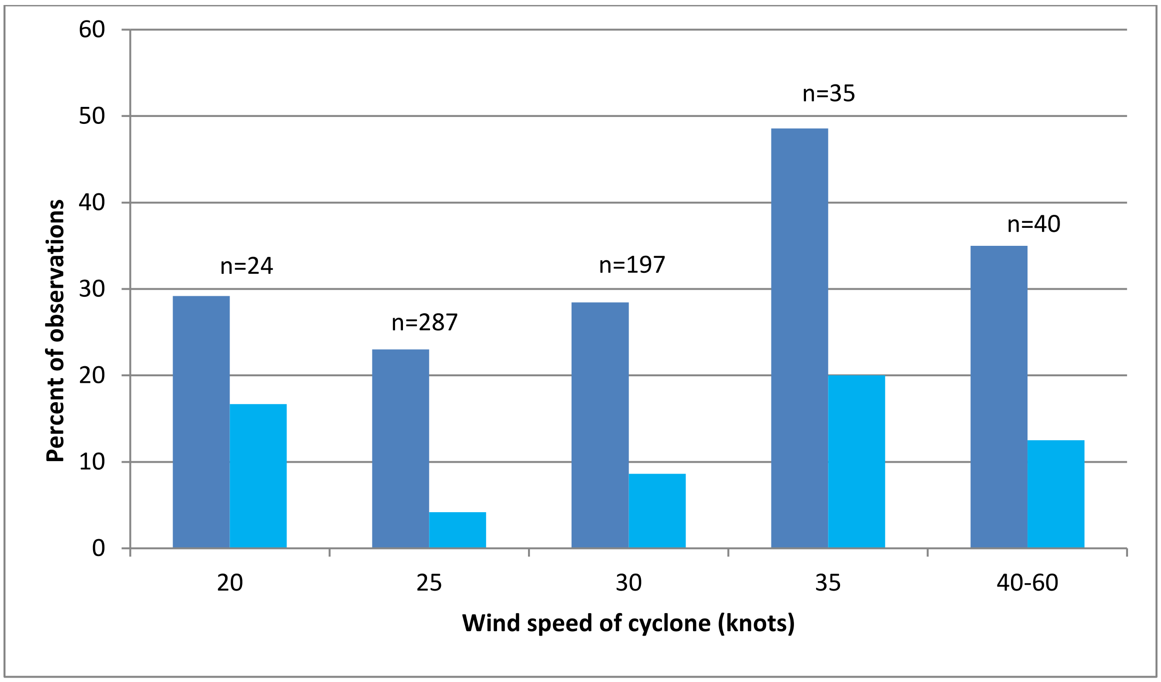

Figure 4. Percent of observations of cyclones at cyclogenesis that were inceptions of intensification events, in relation to wind speed at cyclogenesis. Dark blue indicates intensification events of 15kt/24 h, light blue indicates 30 kt/24 h.

Inceptions of IE occurred in cyclones that were already as strong as 140 kts. For cyclones > 1 d old (> 5th observation) that were not already exhibiting IE, the number of IE initiated at different wind speeds differed from the null distribution (χ^2 = 133.1, df = 17; p < 0.0001; restricted to 25-110 kts to avoid expected values of < 5). Percent inceptions peaked at 30 kts, with another smaller peak at 70 kts (Fig. 5). RIE inceptions also peaked at 30 kts and 70 kt (χ^2 = 38.5, df = 13; p = 0.0002; analysis restricted to 25-90 kts to avoid expected values < 5). This second peak at c. 70 kts was absent in cyclones examined at cyclogenesis because no storms in the sample were this strong at first observation.

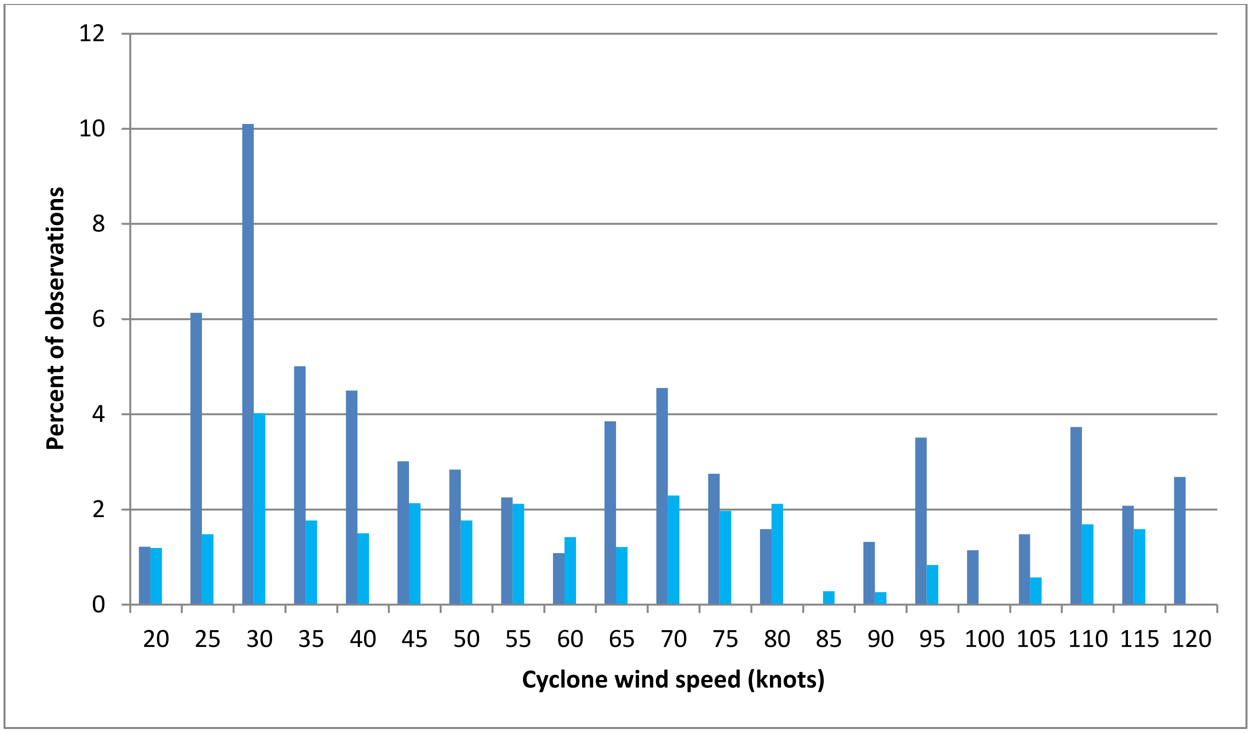

Figure 5. Percent of observations of cyclones that were beginnings of intensification events at different wind speeds, for cyclones ≥ 2 d age. Dark blue indicates intensification at 15 kt/24 h, light blue at 30 kt/24 h. Each bar has n ≥ 110.

Could the apparent tendency for storms > 1 d old to begin intensifying when wind speeds were 30 kt or 70 kt really be some indirect expression of the tendency to do so at particular storm ages? For instance, any tendency that might exist for 30 kt winds to occur on the day of formation could cause 30 kt winds to align with the high inception rates that are found on that day. However, while factoring these age effects into the expected values of the wind speed analysis reduced the chisquared values, these wind speed analyses remained significant for both IE (χ^2 = 86.6, p < 0.0001) and RIE (χ^2 = 31.5, p = 0.0029). The effect of storm age documented earlier in this analysis was also not merely a reflection of this influence of wind speed; age effects remained after wind speed was factored out by the same process for IE (χ^2 = 83.9, p < 0.0001) and for RIE (χ^2 = 23.7, p = 0.0140).

3.5 Recent Strengthening or Weakening

For existing cyclones, the change in wind speed over the preceding 6 h gave some indication that a cyclone was about to begin an IE. Cyclones had only a ~1% chance of commencing an IE immediately after a 6 h decrease in wind speed; values were similar regardless of whether the decline had been -5, -10, or -15 kts. Onset of IE was substantially more likely (7-8%) after 6 n in which wind speed was unchanged. A 5 kt *increase* had a 42% chance of becoming the start of an IE, and a 10 kt increase had an 85% chance. For RIE, likelihood was again very small after declines of -5, -10, and -15 kt (~0-1%), and 2-3% after unchanging winds. Likelihood of an initial increase becoming an RIE gradually rose from after a 5 kt (7%) to a 10 kt (18%) to a 15 kt (29%) increase.

Because of the close relationship between central pressure and wind speed, I assumed associations of changes in central pressure with IE and RIE inceptions would be largely redundant to those associated with changes in wind speed. However, these variables do not vary in lockstep within HURDAT, and a sufficient variety of pressures have occurred at certain wind speeds that it was possible to look for pressure-change effects while holding wind speed change constant. Such analyses were performed for the subsets of the data that had experienced unchanged winds, and that had risen 5 kts.

When winds were unchanged over the preceding 6 h, cyclones that had exhibited pressure declines of -1 to -4 mb had an 10-18% probability of beginning an IE, with the maximum occurring at -1 mb. Greater mb drops than these did not show greater likelihood, with an aggregate IE inception probability of only 5%. Probability was 6% when pressure had not changed, only 2-4% when it had increased by 1-3 mb, and no inceptions occurred after greater mb increases than these. RIE also showed greater odds of inception when pressure had dropped by -1 to -4 mb (~3-8% chance, peaking at -2 mb) than after it had remained unchanged or increased, with no inceptions recorded after increases of ≥ 3 mb.

Smaller variations occurred within the subset of observations that followed 5 kt wind speed increases. Following drops of -1 to -4 mb, cyclones had a 40-47% likelihood of IE inception; this fell to 31% after unchanged pressure, and 18% and 14% after pressure increases of 1 and 2 mb, respectively.

For RIE the odds ranged from ~5-11% following pressure drops (of -1 to -4 mb) and following unchanged pressure, with no clear distinction among them; no RIE developed from observations that reported increasing pressures. Effects of pressure change on inception rates could not be tested for the subset of observations that followed 5 kt declines in wind speed, because too few inceptions occurred to allow subdivision (n=12 total for IE).

3.6 Forward Speed

The number of IE formation events occurring at each forward speed did not differ from that of cyclone observations overall (χ^2 = 4.2, df = 5, p = 0.5159; speed split into six categories of 50 km/d). Neither did RIE inceptions (χ^2 = 3.2, df = 5, p = 0.6690)

3.7 Time of Day

Time of day was analyzed separately for each time zone because they differed in local time among the four HURDAT observation times (0, 6, 12, 18Z). Of the five time-zone specific analyses, the three centered on 45, 60, and 75^{0}W showed evidence of variation of IE inceptions among the four observation times (χ^2 tests with p values of 0.06-0.12; Fig. 6). In each of the five time zones, observations made at 6Z (between 0:00 and 04:00 local time) had more IE inceptions than expected by chance, while those made at 0Z (18:00-22:00 locally) all had fewer than expected. Likelihood of RIE inception varied by time of day in the time zone centered on 45^{0}W (χ^2 = 9.2, p = 0.0271), and appeared to do so in the one at 90^{0}W as well (χ^2 = 5.7, p = 0.1258). However, there was little consistency concerning which times of day showed high and low rates of RIE inceptions in these two time zones.

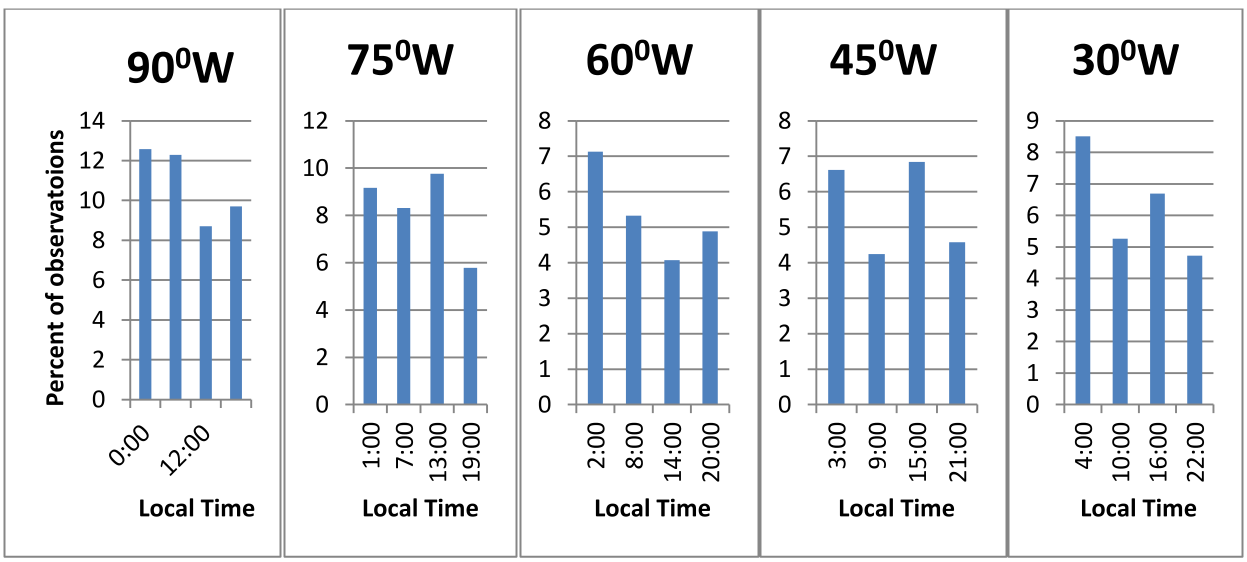

Figure 6. Percent of observations that were inceptions of intensification events (15 kt/24 h) at different times of day, in five time zones.

A time of day influence on intensification could be caused by some diurnal cycle in environmental or internal factors related to storm intensity. However, it could also be the byproduct of cyclogenesis itself occurring unevenly by hour of day, since intensification occurs most often immediately after cyclogenesis (as discussed above). Surprisingly, cyclogenesis was indeed more frequent at some hours of day; this was significant in the 45^{0}W, 60^{0}W, and 75^{0}W time zones (null: equal numbers at each time, all $\chi^2 \geq 9.5$, df = 3, p ≤ 0.024), and the pattern is present though not significant in the other two. In all five zones, the most cyclogenesis events occurred between local times of 07:00 and 12:00, and the fewest between 18:00 and 02:00, with the difference as high as three-fold (in the 45^{0}W time zone). The lack of cyclogenesis from 18:00-02:00 may help explain the infrequency of IE inceptions from 18:00-22:00, since this period would lack observations made at this peak age for IE inception; however, the peak of cyclogenesis from 07:00-12:00 does little to explain the 0:00-04:00 peak in inceptions.

The apparent link of cyclogenesis to time of day suggests that it is possible that the time of day effect on intensification onset could be a byproduct of the storm age effect described earlier in the paper. To investigate this possibility, I employed the same method of incorporating this influence into the chi-square expected values as outlined for previous sections. This actually slightly strengthened the chi-squared statistic for the 45^0W sample (to χ^2 = 6.3, p = 0.1000) and the 60^0W sample (to χ^2 = 10.4, p = 0.0157), while the 75^0W sample was virtually unchanged (becoming χ^2= 6.7, p = 0.0835). The time of day influence on RIE at 45^0W also remained little changed when expected values were adjusted to reflect storm age, strengthening slightly (becoming χ^2= 9.4, p = 0.0247), while the 90^0W result inched closer to significance (becoming χ^2= 6.5, p = 0.0909).

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4. Discussion

This study has shown that the probability of a given cyclone observation constituting the beginning of an IE or RIE was notably high in the Gulf of Mexico and low in the northeast Atlantic, and was most common at and immediately after cyclogenesis. At cyclogenesis, the chances of beginning an IE or RIE was greatest for cyclones with winds of 35 kt; for older cyclones, peaks of inception occurred at both 30 kt and 65-75 kts. When winds were unchanged over the preceding 6h, commencement of an IE was most likely when central pressure had dropped by 1 mb (IE) or 2 mb (RIE). In several time zones, IE inceptions appeared to be least common in the first half of the nocturnal period, and most common between midnight and sunrise.

The tendency for a higher percentage of cyclone observations in the Gulf of Mexico to pertain to cyclones beginning intensification parallels its tendency to have the highest maximum potential intensity values of the six geographical subdivisions during the peak of the hurricane season (based on maps provided by Emanuel http://wind.mit.edu/~emanuel/pcmin/climo.html). As suggested by Rappaport et al. (2010) for systems approaching landfall in the Gulf of Mexico, cyclones may increase or decrease wind speed so as to converge on their current potential intensity. The presence of the Caribbean Loop Current in the Gulf of Mexico may be contributing to high rates of intensification there (Shay et al. 2000). Potential intensities in the northeast Atlantic also tended to be lowest; this was the region where IE and RIE were least likely to begin.

As noted, the tendency of cyclones to begin IE or RIE on the initial date of observation may be attributable to the persistence of the same positive environmental conditions that led to cyclogenesis, persisting early into the cyclone's life. Likewise, the tendency of cyclones to begin IE or RIE more often when their initial observation was 35 kts than when it was 20-30 kts may be because storms that are intensifying rapidly enough to have reached 35 kt sustained speeds at the time of cyclogenesis are likely to be experiencing especially favorable environmental conditions that would also be more likely to sustain an IE or RIE for the next 24 h. It is puzzling that cylones that showed even higher wind speeds at formation did not have even higher rates of IE inception- it might be beneficial for further investigations to examine the circumstances of cyclogenesis that create systems with initial wind speeds of > 35 kts. I also have no explanation for the secondary peak of intensification inceptions at 65-75 kts for older systems. For both these peaks, it might be worth investigating whether gradually declining systems tend to linger at any particular wind speeds. A peak such as that at 65-75 kt could represent speeds less commonly held by declining storms, so that a disprorportionate number with those speeds are intensifying.

Examination of the wind and pressure changes that had occurred immediately prior to an observation indicated that cyclones are seldom able to jump into an IE or RIE directly after weakening, even if it was only by -5 kts or +1 mb. This could indicate that some determinants of intensification, or perhaps wind flows themselves, must overcome some measure of negative momentum as they reverse from negative to positive trends. It could also indicate that environmental conditions generally do not change (by temporal changes or by storm movement into areas with different conditions) quickly enough to produce changes from weakening to strengthening over spans as abrupt as 6 h.

The present study has found that tropical cylcones were least likely to begin intensifying in the nocturnal hours preceding midnight, and most likely in the hours immediately after midnight. Elucidating time of day patterns is complicated by the fact that the four hourly intervals in the HURDAT dataset (0, 6, 12, 18Z) occur at different local times in the five time zones that encompass the bulk of the cyclone-prone region of the Atlantic. I dealt with this problem by analyzing each time zone independently; the temporal pattern was consistent across zones. This study adds to only a handful of previous published works that have reported that tropical cyclones have a diurnal cycle. Konrad (2001) found that landfalling tropical cyclones were more frequent from 06:00-10:00 and 17:00-24:00 LST in the eastern USA, but provided no explanation; his finding is seemingly more related to cyclone existence than the timing of intensification. Kossin (2002) found that cumulonimbus development near cyclone centers peaked near 04:00 and 16:00 LST in satellite imagery, and could confirm no mechanism but suggested one related to the solar semidiurnal atmospheric tide. Thus, Kossin's 04:00 peak of cloud development fits into the early AM peak of intensification in the present study, but his 16:00 peak is not evident in my analyses. The tendency to begin intensifying least frequently during the evening and most during the late night hours was not explicable as a consequence of hourly variations in the timing of cyclogenesis. However, the existence of this temporal pattern of cyclogenesis, though peripheral to the purpose of the study, is worthy of some attention. Existence of a diurnal pattern of cyclogenesis is apparently heretofore unreported in the scientific literature. Cyclogenesis tended to occur between 07:00 and 12:00 LST, and to be least common from 18:00 and 02:00 LST; the breadth of these peaks may be artificially widened by the lack of precision in timing afforded by the 6-h spacing of HURDAT observations. This pattern is deserving of further investigation since accurate forecasting of cyclogenesis remains elusive. One possibility that should be considered is whether any bias has existed in the hourly timing of satellite analyses or of aircraft recognaissance that could lead to newly formed storms most often being detected in the morning hours.

5. Literature Cited

Camp, J., and M. T. Montgomery, 2001: Hurricane Maximum Intensity: Past and Present. *Mon. Wea. Rev.,* **129**, 1704–1717.

Kaplan, John, Mark DeMaria, John A. Knaff, 2010: A Revised Tropical Cyclone Rapid Intensification Index for the Atlantic and Eastern North Pacific Basins. *Wea. Forecasting*, **25**, 220–241.

Konrad, C. E. II., 2001: Diurnal variations in landfall times of tropical cyclones over the Eastern United States. *Mon. Wea. Rev.*, **129**, 2627-2631.

Kossin, J. P., 2002: Daily Hurricane Variability Inferred from GOES Infrared Imagery. *Mon. Wea. Rev.*, **130**, 2260-2270.

Rappaport, E. N., J. L. Franklin, L. A. Avila, S. R. Baig, J. L. Beven, E. S. Blake, C. A. Burr, J. G. Jiing, C. A. Juckins, R. D. Knabb, C. W. Landsea, M. Mainelli, M. Mayfield, C. J. McAdie, R. J. Pasch, C. Sisko, S. R. Stewart, and A. N. Tribble, 2009: Advances and Challenges at the National Hurricane Center, *Wea. Forecasting*, ***24*,** 395–419.

Rappaport, E. N., J. L. Franklin, A. B. Schumacher, M. Demaria, L. K. Shay, and E. J. Gibney, 2010: Tropical cyclone intensity change before U.S. Gulf Coast landfall. *Wea. Forecasting*, ***25*,** 1380-1396.

Shay, L. K., G. J. Goni, and P. G. Black, 2000: Effects of a warm oceanic feature on Hurricane Opal. *Mon. Wea. Rev.*, **128**, 1366– 1383.

Yaukey, Peter, 2011: Wind Speed Changes of North Atlantic Tropical Cyclones Preceding Landfall. *J. Appl. Meteor. Climatol.*, **50**, 1913–1921.